THE UNIVERSITY OF MICHIGAN

Department of Electrical Engineering

Status Report

October 1, 1964 - April 1, 1965

NASA Research Grant NsG 415

"Theoretical and Experimental Investigations of Extremely Dense Plasmas at Very High Energy Densities"

INTRODUCTION

Properties of highly-ionized plasma in the pressure range from 10 to 100 kilobars are being investigated. Techniques have been developed to produce the plasma, and measurements have been made of its temperature, pressure, volume, and internal energy. Various authors have used the Debye-Hückel shielding theory to calculate an equation of state for high density plasma. However their results do not agree with the measured data.

The previous six month report stated that significant data was being accumulated, and that the theoretical analysis of the data should lead to a summary report by this time. However the analysis in terms of the Debye-Hückel theory contradicted the measurements, and the outlook of the research program was changed significantly. The contradiction necessitated extensive cross-checking of measurements to uncover any flaws which might have existed in the experimental techniques, yet the measurements were found to be reliable. As a result, the existing theory was rejected as inadequate to explain the observed phenomena.

BACKGROUND

The dense plasma is produced by discharging a capacitor bank between electrodes which are submerged in water. The atomic constituents of the plasma are primarily oxygen and hydrogen from dissociated water. The discharge path is established by a fine tungsten wire which is stretched between the electrodes. The tungsten is a third, although minor, constituent of the plasma. Diffusion rates are slow enough that electrode contamination is not important.

A pressure of 10 kilobars is obtained in the plasma because of the inertial restraint of the water which surrounds the plasma column. The pressure is generated when the expanding column displaces the water to produce a radially directed shock wave.

Plasma pressures up to 100 kilobars are obtained by detonating an explosive charge in the water near the plasma column. The explosive generates a shock wave of 100 kilobars of pressure which sweeps across the plasma column to envelop it in the region of high pressure behind the shock front.

For both pressure levels, measurements are taken of pressure, temperature, current, voltage, and column growth rate. Radiative and mechanical energy losses from the plasma are subtracted from the electrical energy delivered to the plasma to leave the net internal energy. Also the internal energy is computed theoretically from temperature, pressure, and volume; and the theoretical result is compared with the experimental finding.

PROGRESS AND RESULTS

Measurements taken last fall were found to be inconsistent with the equation of state based upon the Debye-Hückel shielding theory. The measured internal energy of plasma at 7 kilobars was about five times as large as the theoretically predicted value. However at 100 kilobars the theory was in much closer agreement with experiment than at the lower pressure.

Because of the discrepancy, the experimental program was extended and modified in ways which might expose any faulty measurements. Both electrode design and instrumentation were changed. The result of the extended program was to improve the accuracy of the measurements, but not to eliminate the discrepancy which led to the extension. The original data were basically correct.

Tests have been performed at different rates of current rise in the plasma column, without the use of chemical explosives. The pressure developed was dependent upon the rate of rise, and varied from 5 to 10 kilobars. Typical data are shown in Table 1. For the conditions of temperature and pressure shown there, theory predicts an internal energy of approximately $4 \cdot 10^3$ joules/cm^3.

TABLE 1

MEASUREMENTS FOR UNDERWATER SPARK WITH di/dt = 10^{11} amp/second

Time (microseconds)	0.6	1.0
Pressure (kilobars)	10.7	11.6
Temperature (K°)	32,000	32,000
Internal Energy (joules/cm^3 x 10^{-3})	17.6	12.4

The plasma at 100 kilobars has a temperature of 10,000°K, which is much lower than the temperature of the 10 kilobar plasma. Because of the strong dependence of ionization on temperature, the 100 kilobar plasma probably has a lower concentration of free electrons. Further measurements and calculations are being performed to obtain a more accurate description of the 100 kilobar plasma than the completed measurements provide.

A possible reason for the failure of the Debye-Hückel theory is that the electron density in the 10 kilobar plasma is very high. Simple two body collisions are rare because of the high density. The electron quantum wavelength, h/p, is approximately equal to the interparticle spacing. The possibility of collective oscillations among charged particles might account for errors in the calculation of internal energy.

If high electron density is the explanation for the discrepancy, then the 100 kilobar plasma, with lower electron density, should be more accurately described by theory than the 10 kilobar plasma. To the extent that calculations have been completed at this time, the 100 kilobar plasma is described better by the theory.

Certain instabilities have been observed in the 100 kilobar plasma. If the 100 kilobar pressure from the chemical explosive is established in the water surrounding the tungsten initiating wire before the electrical discharge is begun, the plasma formation is very irregular. To avoid this instability, the discharge is initiated before the high pressure is established. A uniform plasma column is formed and then is swept by the high pressure shock wave. The column grows stably for about 3/4 of a microsecond, but then the column splits into two parallel current carrying paths. Before the split, the column has an elliptical cross-section because of the compression from the shock wave. The split is such to divide the ellipse along its minor axis.

Magnetic pinch pressure is discounted as a reason for the instabilities because its magnitude is only a few kilobars as compared with the mechanical pressure of 100 kilobars. Rather the conductivity mechanism would seem to be involved in the explanation.

FUTURE PLANS

The immediate plans are to make further measurements at 100 kilobars in order to obtain a more complete set of data, and to consider the nature of a theory to replace the Debye-Hückel theory. The work will then be reported in detail. The report will be used as a doctoral thesis for Mr. Robinson as well as a technical report to NASA.

Now that equipment is available for high pressure plasma studies, the present investigations can be extended in several ways with a modest expenditure of funds. The completion of the present phase of study will bring significant results, yet many unanswered questions will remain. By further investigation some of the more interesting questions can be considered in detail.

Under certain conditions, the plasma configuration deviates from the ideal shape of a uniform cylinder. A study of the nature and causes of the deviations should lead to a more complete understanding of the plasma than is obtained with the present methods of analysis.

One of the most interesting deviations is the irregular plasma formation which occurs when a pressure of 100 kilobars is established in the water about the initiating wire before the discharge begins. For this case, explanation in terms of a magnetic instability is not acceptable because the mechanical pressure greatly exceeds the pinch pressure. A study of photographs reveals that regions of hot plasma are separated from each other by regions of cooler plasma. Furthermore, both the hot and cool plasmas are current conducting media. The situation strongly suggests the existance of two different phases with different conductivity mechanisms.

The splitting of the 100 kilobar plasma column into two columns is an unusual phenomenum. The splitting, which has occurred under various experimental conditions, warrents further study.

Plasma which has no explosive confinement has exhibited occasional instabilities. A small kink in the initiating wire has produced a kink instability in the plasma column. Also sausage instabilities have been observed. With no explosive, the pinch pressure is a significant fraction of the total pressure, and magnetic instabilities are not unreasonable. With an increase in the rate of current rise, the magnetic pressure could become dominant, and underwater spark behavior might be changed significantly.

The possibility of generating thermal neutrons has been considered for a plasma formed in heavy water. At 100 kilobars, a temperature somewhat in excess of 10^6 °K would be a threshold for neutron production. Energy losses from the plasma would make the high temperature difficult to obtain, but new techniques, perhaps involving a high pressure pinch, might solve the energy loss problem. The pinch pressure currently being produced is greater than that in typical thermonuclear experiments.